SEEING SPOTS

DETAILED STUDY WITH LEMIEUX SOLVES A PUZZLE ABOUT WHAT SOLAR PROCESSES GOVERN THE DECAY OF SUNSPOTS
To compare the Sun to spaghetti doesn’t occur to many of us, but spaghetti is what comes to mind when Juri Toomre thinks about solar magnetism.

“One of the great mysteries is how the Sun builds and rebuilds its magnetic fields,” says Toomre, professor of astrophysics and planetary science at the University of Colorado. He has led several “grand challenge” research efforts on solar turbulence and magnetism and has spent decades working to better understand solar phenomena such as sunspots, the surface blotches that are still a puzzle despite hundreds of years study. What processes cause them? Why do they show up, like clockwork, every 11 years? The answers, says Toomre, have to do with spaghetti.

Blasts of ionized gas inside the Sun create powerful magnetic fields that twist through the solar interior like bundles of spaghetti. Occasionally, the ends of these churning bundles push their way to the Sun’s surface, where they appear to us as sunspots. Over time, the Sun’s rotation and convection and the effects of other nearby magnetic fields wrench the bundles apart. When this happens, like spaghetti cooked too long, the magnetic field turns to mush and its corresponding sunspot fades from view.

When sunspots break up, they do it with a flourish that can create problems on Earth. With the relatively sudden release of magnetic energy, the Sun also can eject huge blobs of ionized gas into space. At about a million miles an hour, a few days and 93 million miles later, these solar flares can cripple Earth telecommunications and military operations. “These innocent-looking sunspots,” says Toomre, “are the footprints for big magnetic structures in the corona, and if a coronal mass ejection comes toward Earth, this is 200 billion tons of plasma, enough to bring down a power grid.”

“Being able to forecast these storms is a major area of research activity,” says Marc DeRosa, a physicist at the Stanford-Lockheed Institute for Space Research, Palo Alto, California, “and by understanding the evolution of the surface magnetic fields, we hope to gain insight into how these major eruptive events occur.”

To that end, DeRosa, who participates in Toomre’s research group, and his Stanford-Lockheed colleague Neal Hurlburt, turned to LeMieux, PSC’s terascale system, for detailed simulations of how these spaghetti-like, magnetic-field bundles get cooked by turbulent fluid inside the Sun. With a series of computations, they appear to have resolved a vexing question about what solar processes are in charge when the bundles come undone.

ROILING AND BROILING

For nearly five centuries, since Galileo and others first observed them around 1610, sunspots have attracted the attention of scientists. We’ve learned that they appear every 11 years, usually in matched pairs of opposed magnetic-field polarity. Because the polarities switch every 11 years, a complete cycle is 22 years. “Despite being embedded in the roiling and broiling of the Sun’s outer layers,” says DeRosa, “sunspots display a remarkable amount of order over long time scales.”

Sunspot evolution is governed by the “solar dynamo” — the Sun’s convective, magnetic churning processes that continually shear and twist magnetic fields. At the Sun’s core, a 16-million-degree centigrade nuclear furnace forges helium from hydrogen atoms. Energy slowly diffuses outward until, about two-thirds of the way to the surface, it reaches the “convection zone.” There, buoyant gas carries the radiant energy to the solar atmosphere, where it releases as light and the fluid cools. Repeated hot upwellings and cooler sinkings of this mixture appear on the Sun’s surface as tightly packed, cell-like granules.

At the inner border of the convection zone is the tachocline, a layer of violent shearing that gives birth to solar magnetic fields. The tachocline organizes magnetic fields, says Toomre, much like a cotton gin combs cotton into fibers. These magnetic-field “fibers” are called flux, and bundles of parallel flux — which have a negative and positive pole — are flux tubes.

These images from NASA’s SOHO satellite show sunspots in early September 2001. Because they are cooler than the rest of the Sun’s surface, sunspots are dark in visible light (a). An ultraviolet image (b) from about the same time, shows sunspots as visible traces of magnetically active regions.
**FLUID VELOCITY AND MAGNETIC FIELD**

The vertical flow velocity (left) and magnetic field (right) from the same region show gradual decay of the magnetic field. “The network of downflow lanes changes continuously as new convection cells emerge and old cells die out, causing the magnetic network to evolve,” says DeRosa. “As fragments of opposite polarity collide, the field cancels.”

**THE SIMULATION DOMAIN**

These perspective views represent a radial slab near the top of the solar convection zone. In this view, the flow (top) has evolved past the initial startup and several convection cells have established themselves, with broad upflow centers (white) surrounded by a network of narrow downflow lanes. The magnetic fields (lower) show a cross-section of two opposite-polarity flux tubes. “At regions of strong magnetic flux,” says DeRosa, “the flow velocities are noticeably lower.”
Within the convection zone, the flux tubes and the up–down thermal churning of convection are pitted against each other. “Convection continually buffets flux tubes and gradually breaks them up,” says DeRosa. “At the same time, the strong magnetic field of a flux tube works to inhibit convective motions.”

How sunspots maintain their coherence as long as they do—several days or weeks—has puzzled scientists, given that the flux tubes are embedded in the extreme turbulence of the convection zone. The expectation, says DeRosa, is that “turbulent decay” would govern, and the magnetic fields would decay faster than they do.

“Instead, the magnetic fields decay more in accord with “Ohmic decay,” a slower process in which the flux tube’s field diffuses over time through interaction with flux tubes of opposite polarity. Until now, computational simulations of this process, which were limited to 2D, failed to solve the puzzle, since they indicated, in accord with expectation, that turbulence—rather than Ohmic decay—governed the process.

SEEING INSIDE THE SUN
Since there’s no way to step inside the Sun and look at the solar dynamo, computational simulations are essential for detailed understanding. “Most of our knowledge of convection within the Sun,” says DeRosa, “is limited to what is measured at the solar surface. Because we can’t see below the Sun’s atmosphere, we have only a general picture of how the fluid is moving.”

With access to LeMieux, it became possible for DeRosa and Hurlburt to undertake much more computationally demanding—and realistic—3D simulations. “LeMieux’s fast interprocessor communication,” says DeRosa, “was critical to this work.”

To get an in–close look, they modeled a curved, spherical slab near the top of the convection zone, a solar domain large enough for a bipolar paired set of flux tubes, the surrounding magnetic field and convective motion. Using 32 LeMieux processors, they ran a series of three simulations, testing different parameters, with each simulation requiring about 700 hours of computing time.

The results: Contrary to 2D simulations, the more realistic 3D study shows magnetic-field decay that matches more closely with observed decay. “Despite the presence of turbulent convection,” says DeRosa, “the decay is closer to the Ohmic rate. This helps to explain why solar active regions persist for several days to weeks.”

“These are elegant calculations,” says Toomre, “that take us closer to understanding the mystery of the solar dynamo.” DeRosa thinks the Ohmic rate may preclude the convection, contrary to expectation, is strongest between the opposed-polarity flux tubes and may help to keep them separate, inhibiting turbulent decay.

With future simulations on LeMieux, he plans to extend the spherical slab upward to include the solar corona and to couple the interactions between the convection zone and the corona, the part of the Sun we see from Earth. In the corona, as compared to the convection zone, the magnetic field is much stronger in relation to the energy of fluid flow. To combine detailed models of these two physically different regions is a numerically challenging problem that no one has tried, and that presents another test for LeMieux. (LW)

MORE INFORMATION:
http://www.psc.edu/science/sunspots.html